Searches for long-lived particles at the LHC

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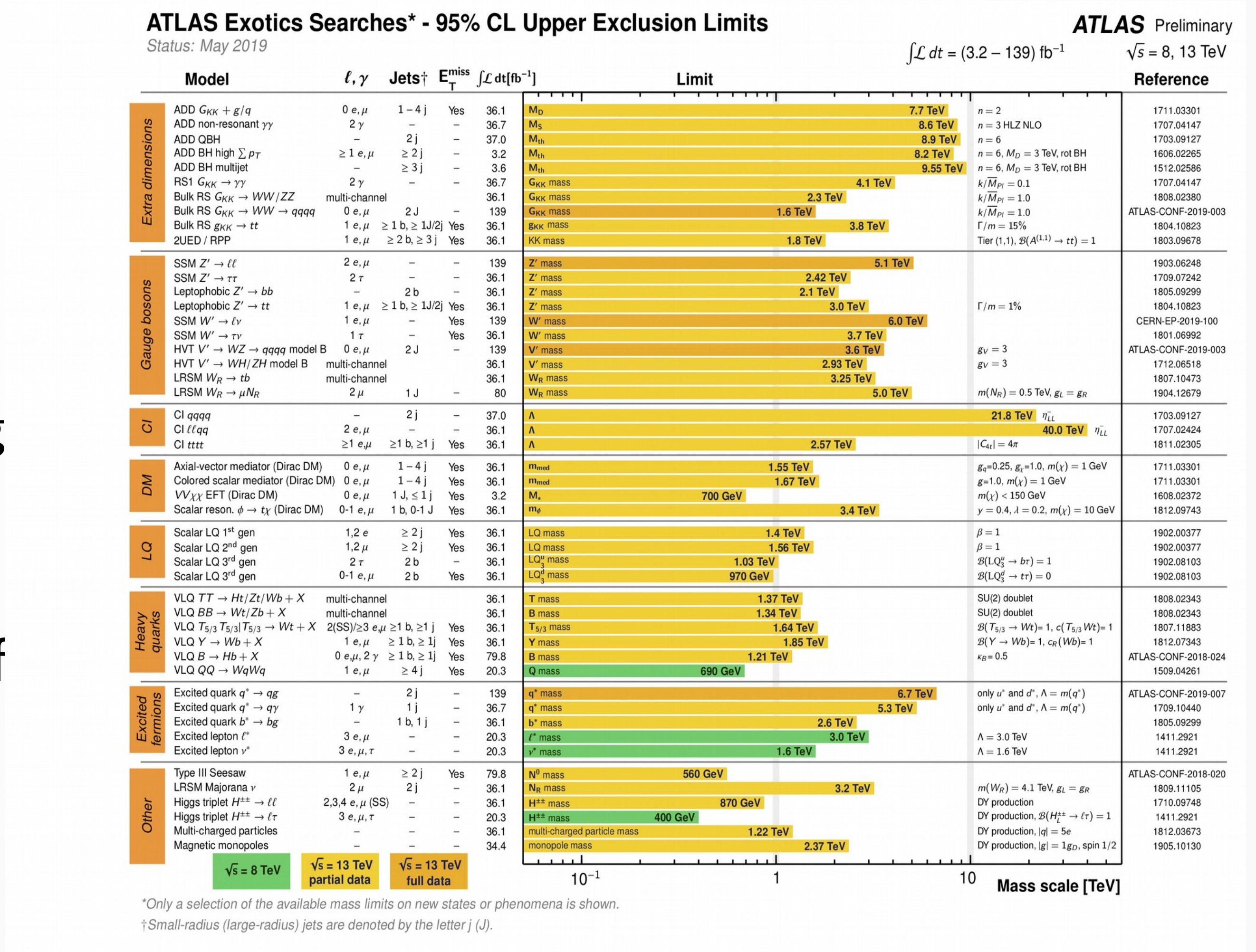
Conventional searches

- ATLAS and CMS have performed numerous new physics searches, probing a large region of parameter space for a variety of BSM models:
  - In many cases, mass limits are now approaching or, in some cases, exceeding 10 TeV
- But remember, every search includes baked-in assumptions on the nature of new particles:
  - One of the most ubiquitous is that new particles will be short-lived

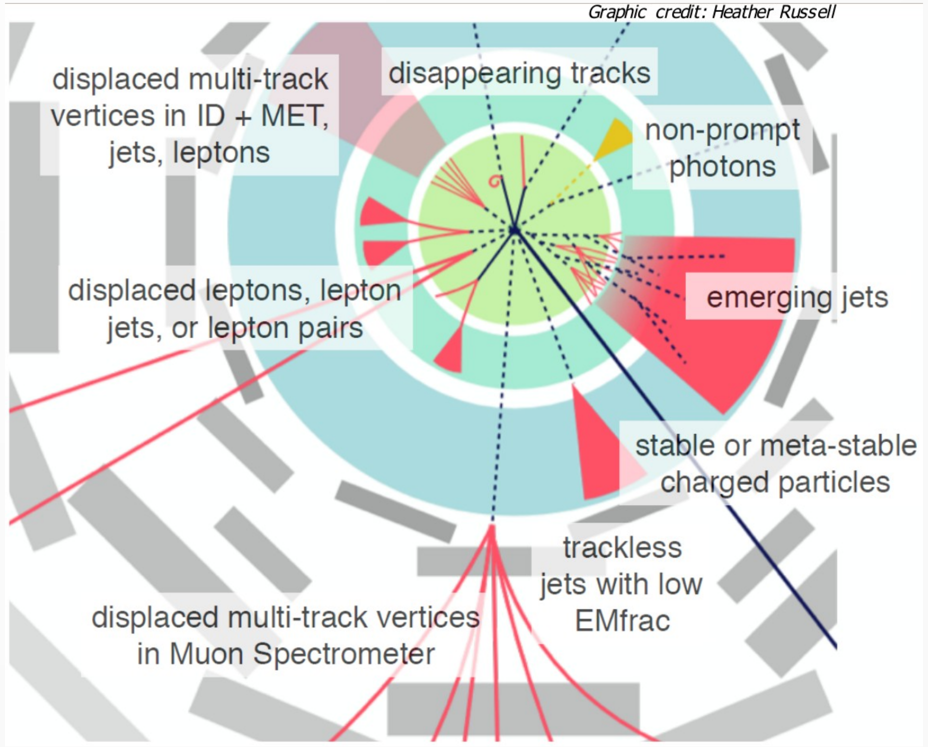


Long-lived particles

- Challenging these assumptions is more important than ever as we continue to find no significant evidence of BSM physics at the LHC
- Long-lived particles (LLP) in particular are predicted by a wide range of theoretical models:
  - Small coupling constants --- e.g., SUSY with R-parity violating (RPV) couplings
  - Very off-shell intermediate decay products --- e.g., split SUSY where heavy intermediate squarks enhance the gluino lifetime
  - Limited decay phase space --- e.g., AMSB SUSY where the lightest neutralino and chargino are nearly degenerate

- Experimentally, these models result in a rich cornucopia of possible signatures in our detectors
- Both ATLAS and CMS have extensive programs of searches for these signatures and have set limits on them across many orders of magnitude in lifetime

Graphic credit: Heather Russell



Recent searches

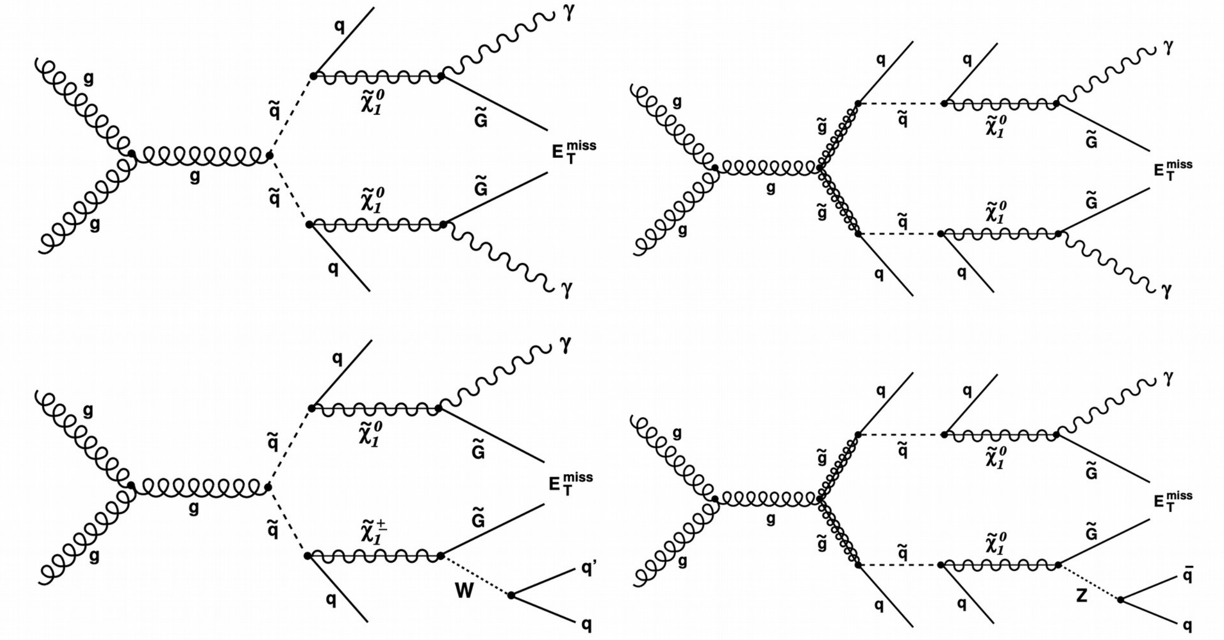
- Far too many searches just from the past year to cover in detail here:
  - A few of the most recent results from ATLAS and CMS will be highlighted here
  - The rest are linked to their public results pages in the table
- See also complementary talks at this workshop:
  - Dark sector searches at the LHC by M. Saimpert (later in today's session)
  - Prompt RPV searches at the LHC by R. Carney (tomorrow's session)

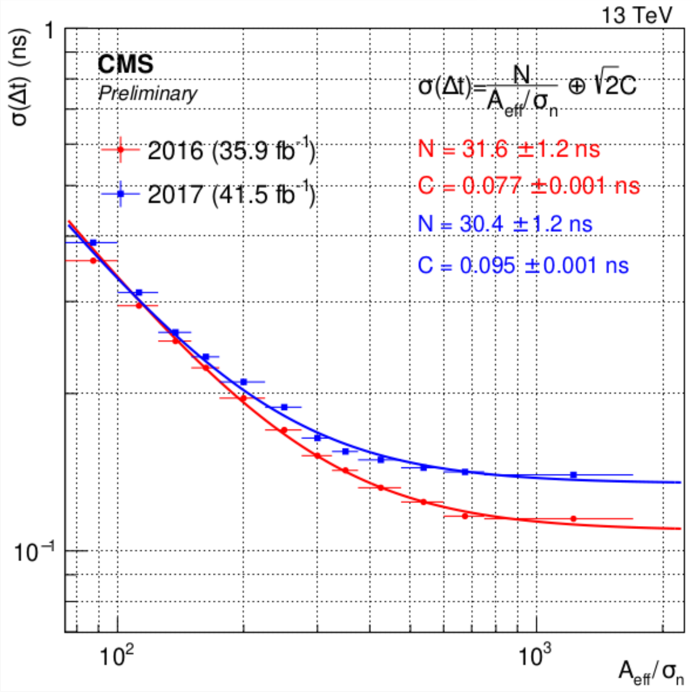
Search	Experiment	Luminosity [fb^{-1}]
Emerging jets	CMS	16.1
Z + displaced jet in calo.	ATLAS	36.1
Displaced jets in MS	ATLAS	36.1
Displaced jets	CMS	35.9
Multi-charged particles	ATLAS	36.1
Heavy charged particles	ATLAS	36.1
Displaced jets in calo.	ATLAS	10.8/33.0
Displaced vertex + displaced muon	ATLAS	136
Heavy neutral leptons	ATLAS	32.9-36.1
Highly ionizing particles/ monopoles	ATLAS	34.4
Delayed jets	**CMS**	**137**
Displaced lepton vertices	**ATLAS**	**32.8**
Dark photon jets	**ATLAS**	**36.1**
MT2 + disappearing track	CMS	137
Delayed photons	**CMS**	**77.4**

Delayed photons

Submitted to PRD
arXiv:1909.06166

- Search for neutral LLPs decaying to photons:
  - Photons arrive late at the ECAL
- Delayed photons can occur, e.g., in GMSB:
  - Long-lived neutralino produced via squark/gluino pair production
  - Decay to photons ⇒ one or two delayed photons



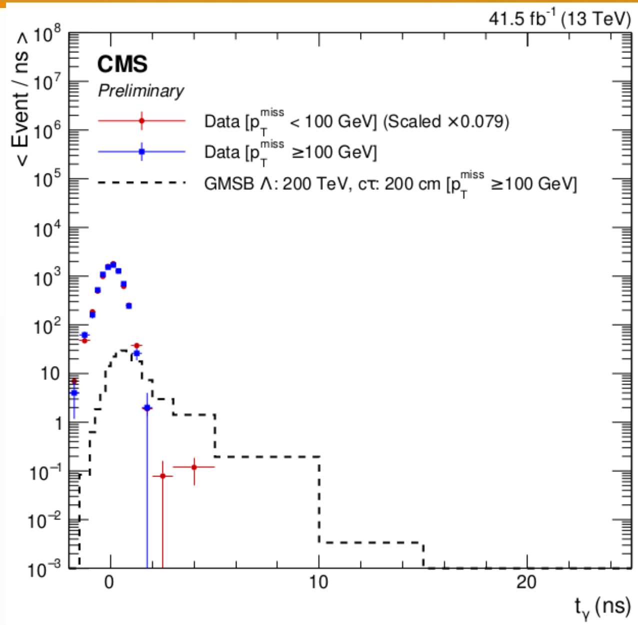


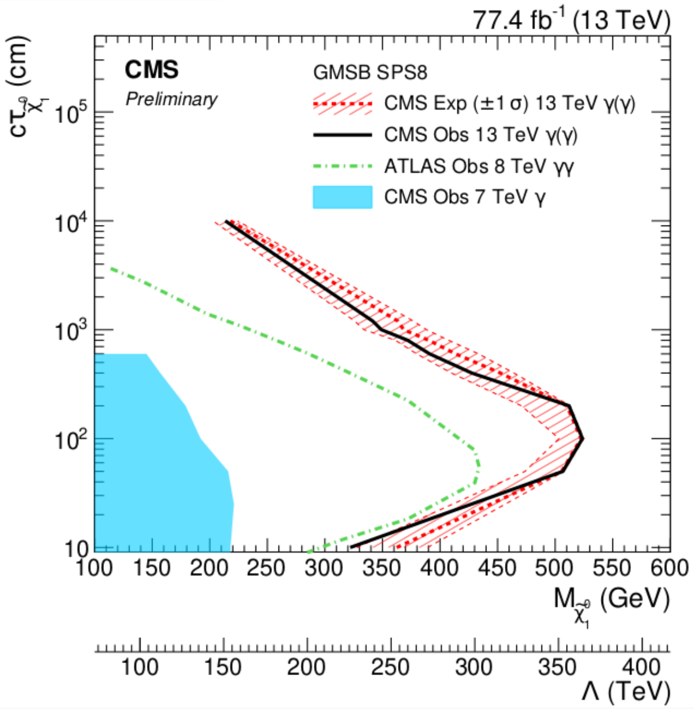
- Photon arrival time (t_γ) is one of the main observables:
  - Weighted average of timestamps from each ECAL crystal in the photon cluster
  - Weighted by ECAL time resolutions obtained from dedicated measurement as a function of effective crystal amplitude

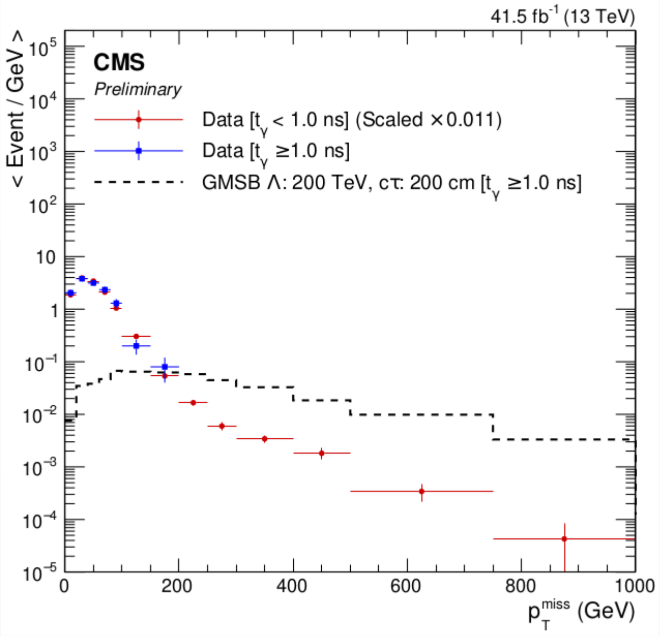
Delayed photons

Submitted to PRD
arXiv:1909.06166

- The other main observable is missing transverse momentum (p_T^{miss})
- Background estimated using an ABCD method with t_γ and p_T^{miss}:
  - Fit for background yield and signal strength simultaneously in all four regions
  - Background is lowest in high t_γ, high p_T^{miss} region, making it the most sensitive
- Observation in each region consistent with expected backgrounds
- Limits placed on long-lived neutralino production in the context of GMSB



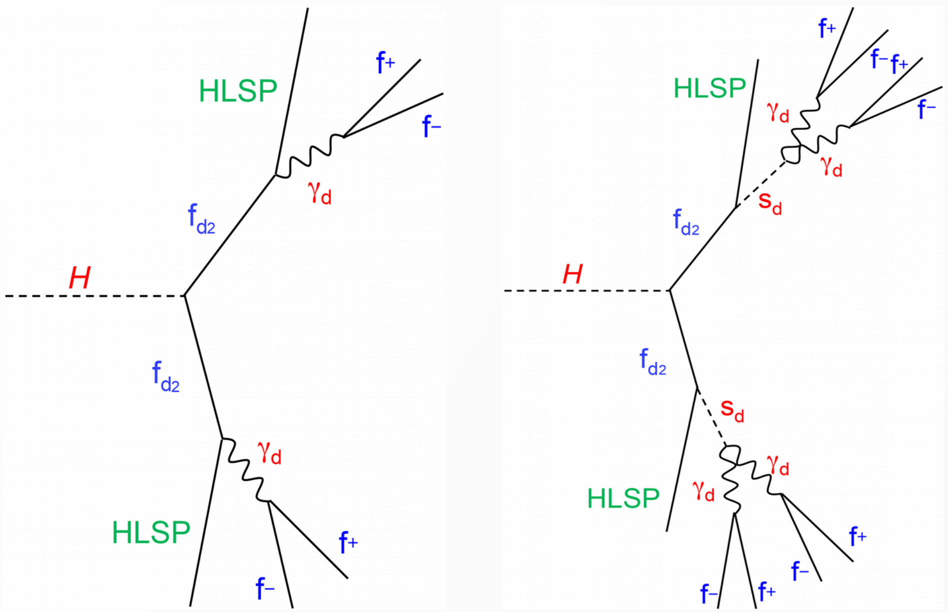




Displaced dark photon jets

Submitted to EPJC
arXiv:1909.01246

- Search for displaced decays of dark photons produced from the decay of the Higgs boson to dark fermions:
  - Targets collimated fermions coming from the decay of a light LLP (dark photon jet (DPJ))
  - Very different signature from the decay of a heavy LLP
- Two types of DPJs considered, each with distinct backgrouds:
  - BDTs used to isolate signal
- Three signal regions defined based on the types of the two leading DPJs in selected events:
  - µDPJ-µDPJ, µDPJ-hDPJ, or hDPJ-hDPJ

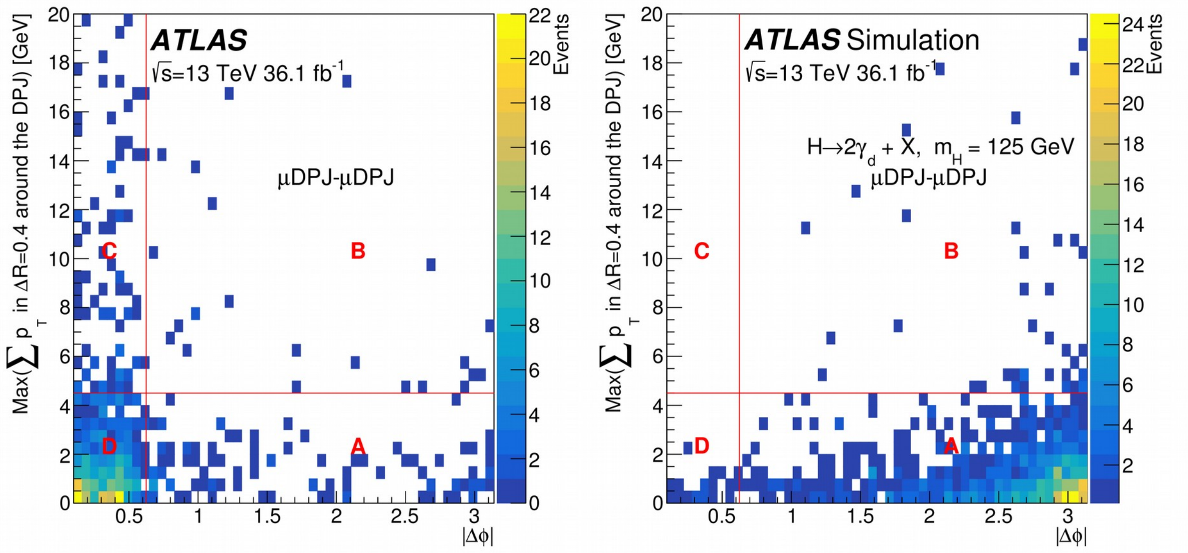


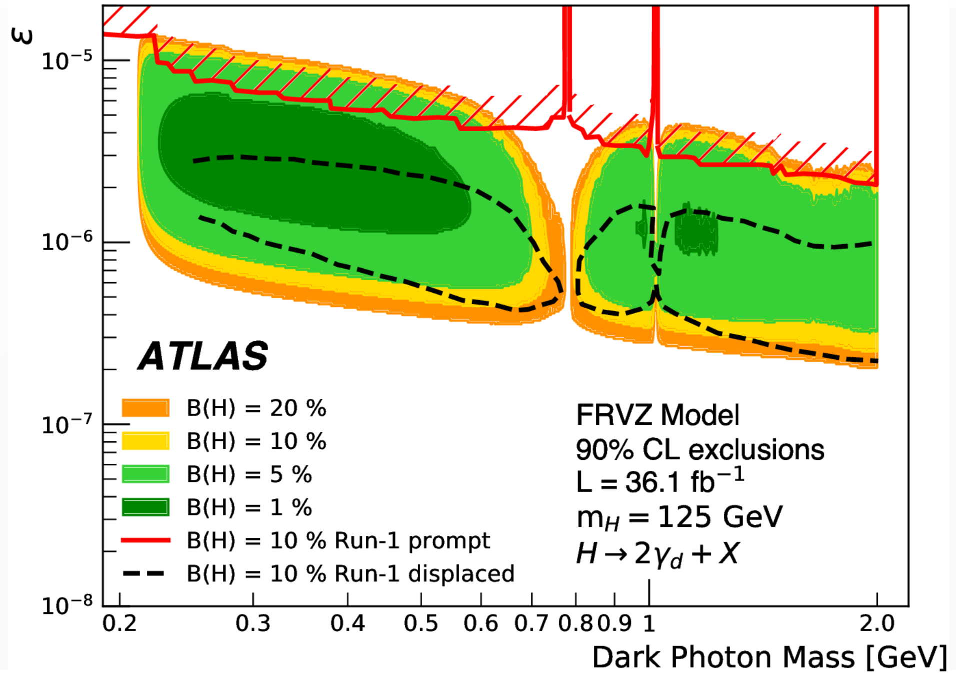
Type of DPJ	Definition	Dominant background
Muonic-DPJ (µDPJ)	≥2 muons within ΔR < 0.4	Cosmic muons
Hadronic-DPJ (hDPJ)	Hadronic jet with ECAL energy fraction < 0.4	QCD multi-jet events

Displaced dark photon jets

Submitted to EPJC
arXiv:1909.01246

- Background from cosmic rays estimated using empty-bunch-crossing data
- Multi-jet background estimated using ABCD method:
  - Maximum track isolation (low in signal)
  - |Δϕ| (high in signal)
- Observation consistent with expectation in all three signal regions
- Limits placed on long-lived dark photon production via Higgs decay:
  - Kinetic mixing term, ε, between SM and dark photon fields determines dark photon lifetime
- Very nicely complements results from searches for prompt and displaced dark photons from Run 1

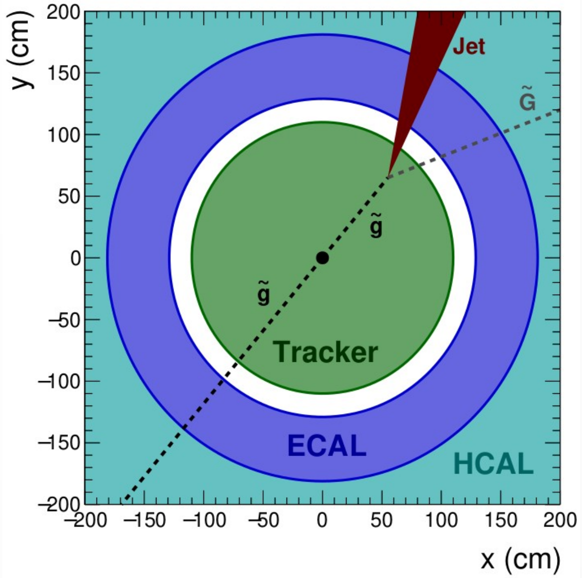


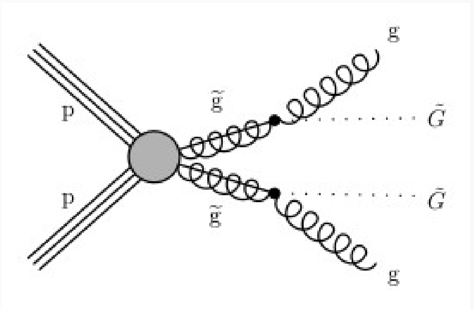


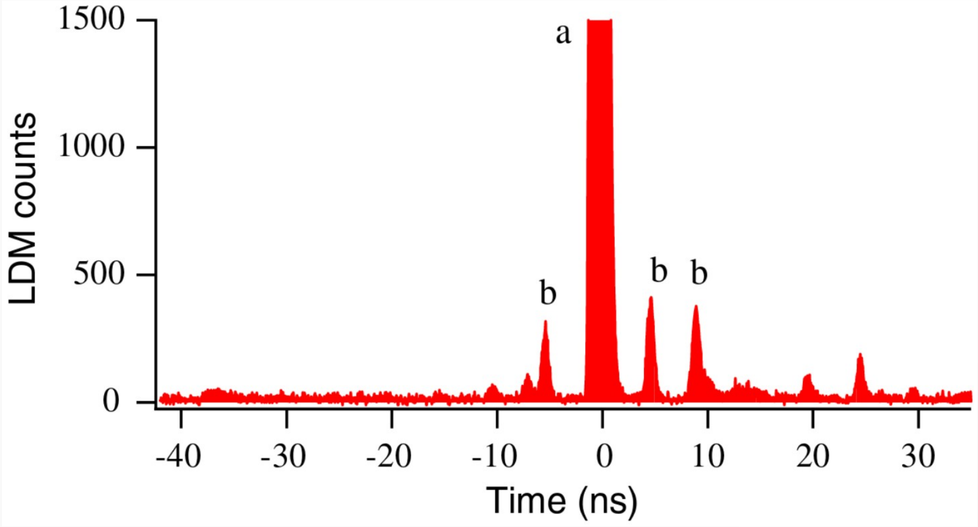
Delayed jets

Phys. Lett. B 797 (2019) 134876

- Search for LLPs decaying to hadronic jets using the full Run 2 data set:
  - Shower would arrive late at the ECAL
  - Targeting decays beyond the acceptance of the tracker
- This signature can occur, e.g., in GMSB:
  - Pair produced gluinos become long-lived via the small coupling to the gravitino
- First search to look for this kind of topology, and the first to use ECAL timing to tag delayed jets







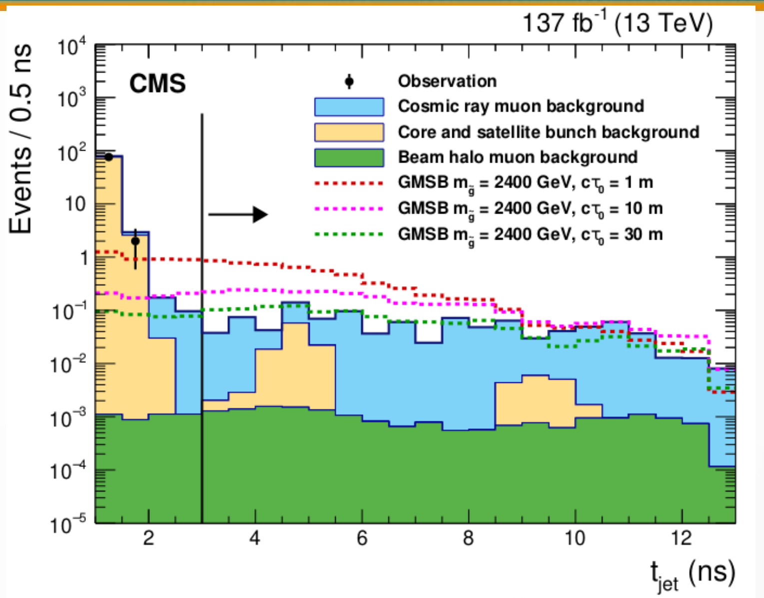
Phys. Rev. Spec. Top. Accel. Beams 15 (2012) 032803

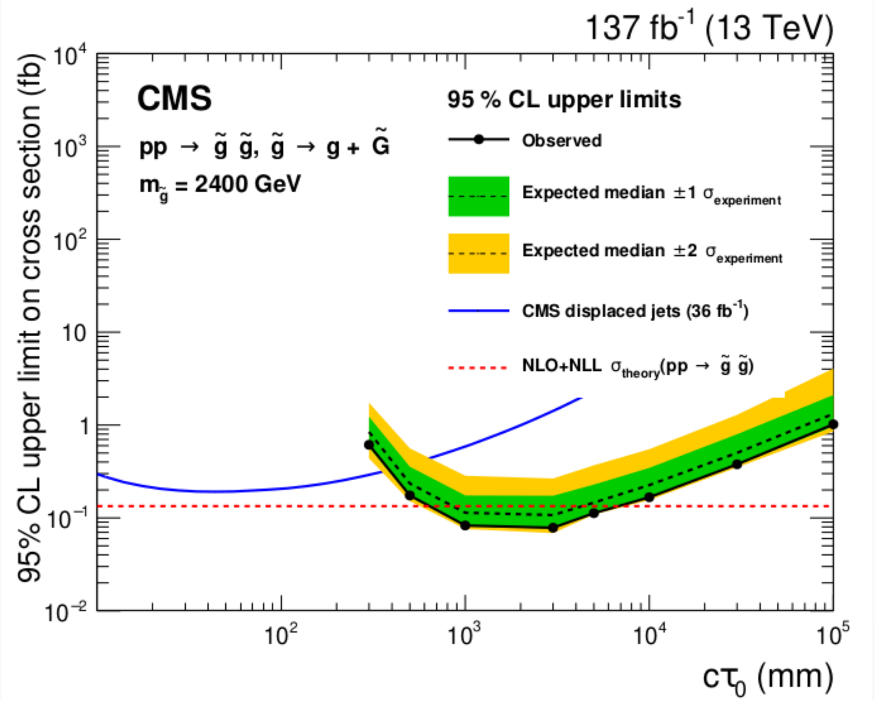
- Extensive quality selections remove a wide array of backgrounds:
  - Direct interactions with ECAL front-end
  - Satellite bunches
  - Beam halo deposits in ECAL
  - Cosmic muon deposits in ECAL
  - Noise deposits
- These selections reduce the background by many orders of magnitude

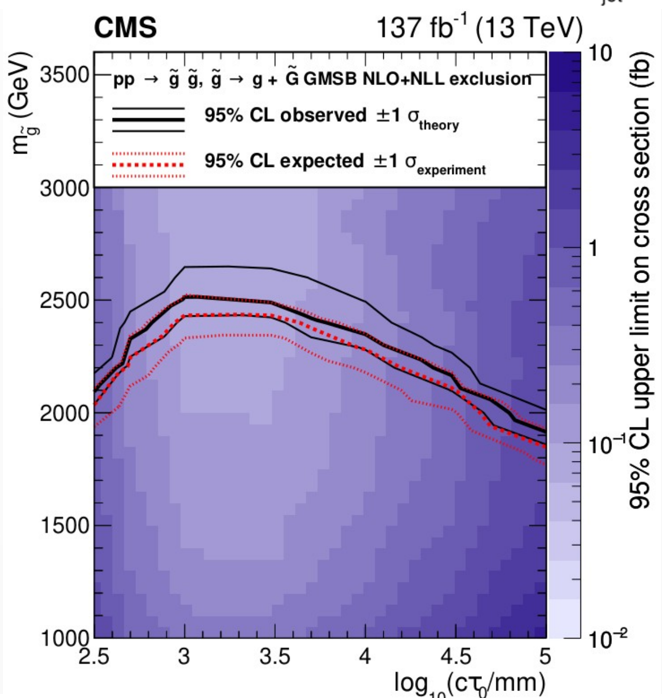
Delayed jets

Phys. Lett. B 797 (2019) 134876

- Remaining background from beam halo, satellite bunches, and cosmic muons:
  - Each predicted with independent ABCD methods defined with the cleaning variables targeting each background
- 1.1-1.1+2.5 events predicted in signal region (t_{jet} > 3 ns):
  - No events observed
- Limits placed on long-lived gluino production in the context of GMSB:
  - Beautifully complements the previous displaced jets search from CMS



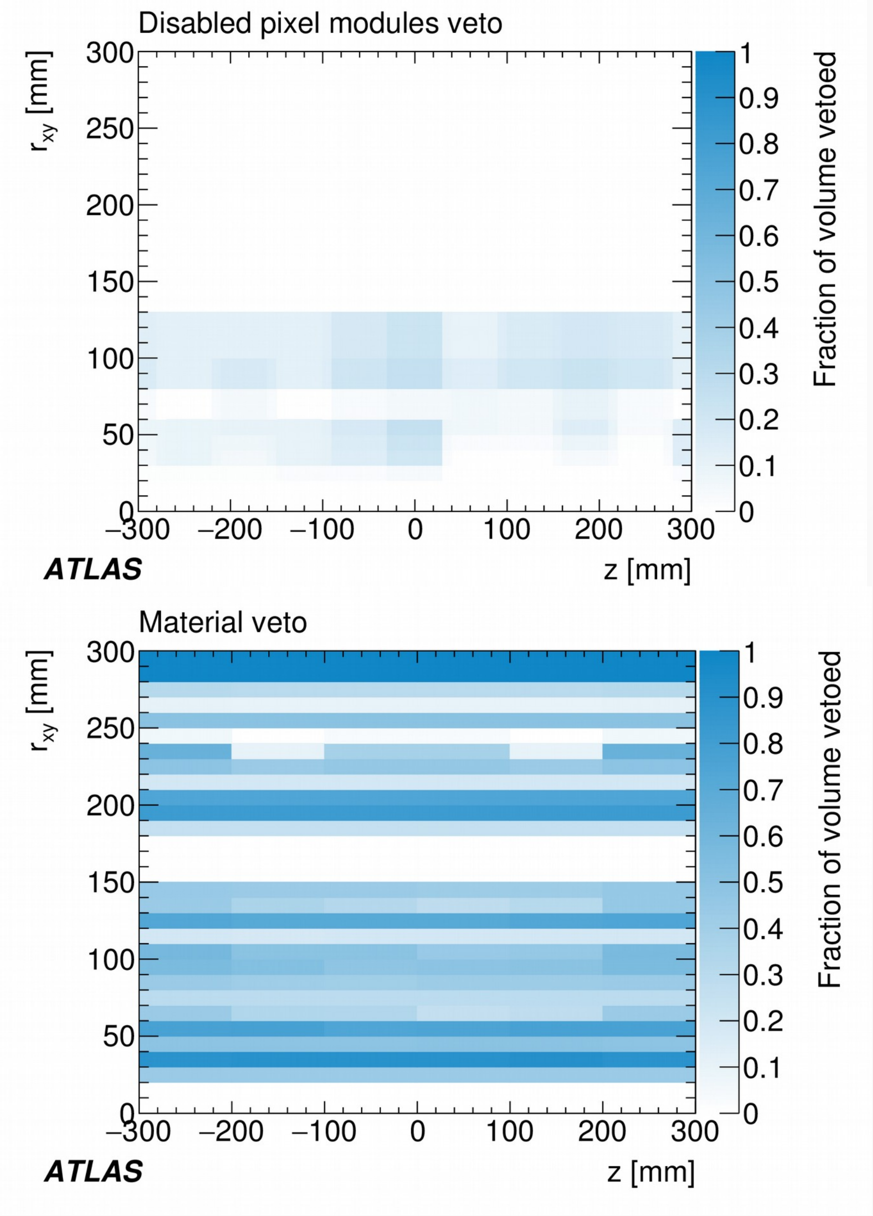




Displaced lepton vertices

Submitted to PLB
arXiv:1907.10037

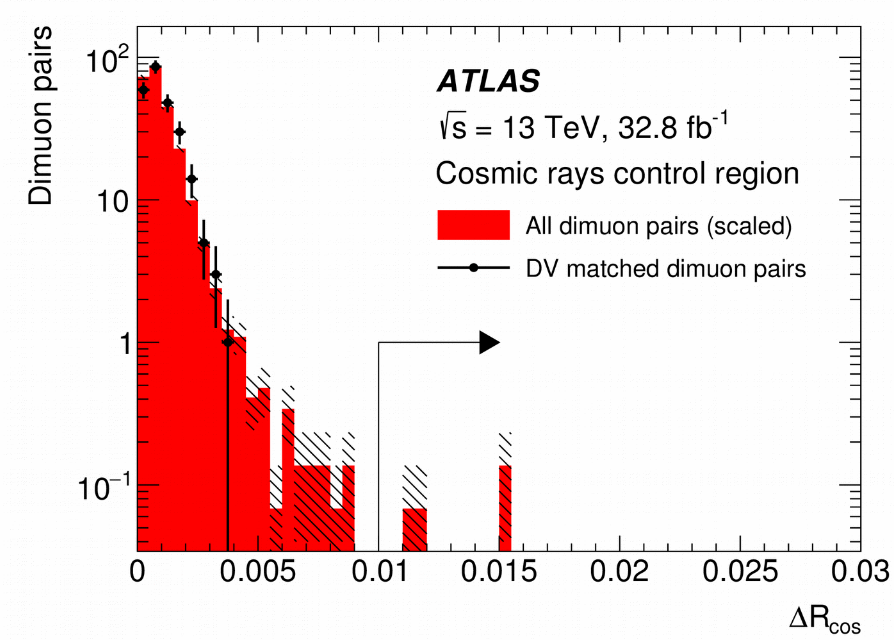
- Model-independent search for long-lived particles decaying to pairs of leptons (e/μ)
- Large radius tracking/dedicated displaced vertex (DV) reconstruction run on events passing preselection:
  - DVs required to be associated with two, oppositely-charged leptons
  - DVs directly in front of disabled pixel modules vetoed
  - DVs with electrons originating in material vetoed



Displaced lepton vertices

Submitted to PLB
arXiv:1907.10037

- Background dominated by muons from cosmic rays reconstructed as two back-to-back muons:
  - Reject lepton pairs with
    $$\Delta R_{\cos} = \sqrt{(|\Delta\phi| - \pi)^2 + (\eta_1 + \eta_2)^2} < 0.01$$
- Remaining background estimated with a control region of back-to-back muons not required to form a DV:
  - Normalized using the subset with a matched DV
- Subdominant background from randomly crossing tracks:
  - Estimated by randomly mixing tracks from separate events to measure how often they form a DV

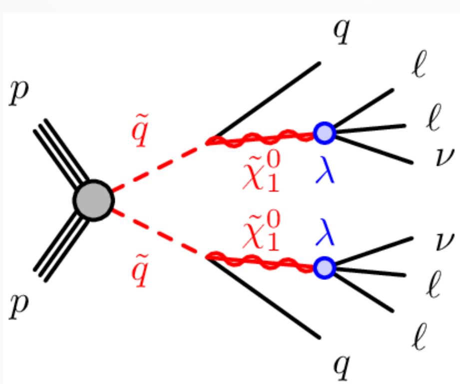


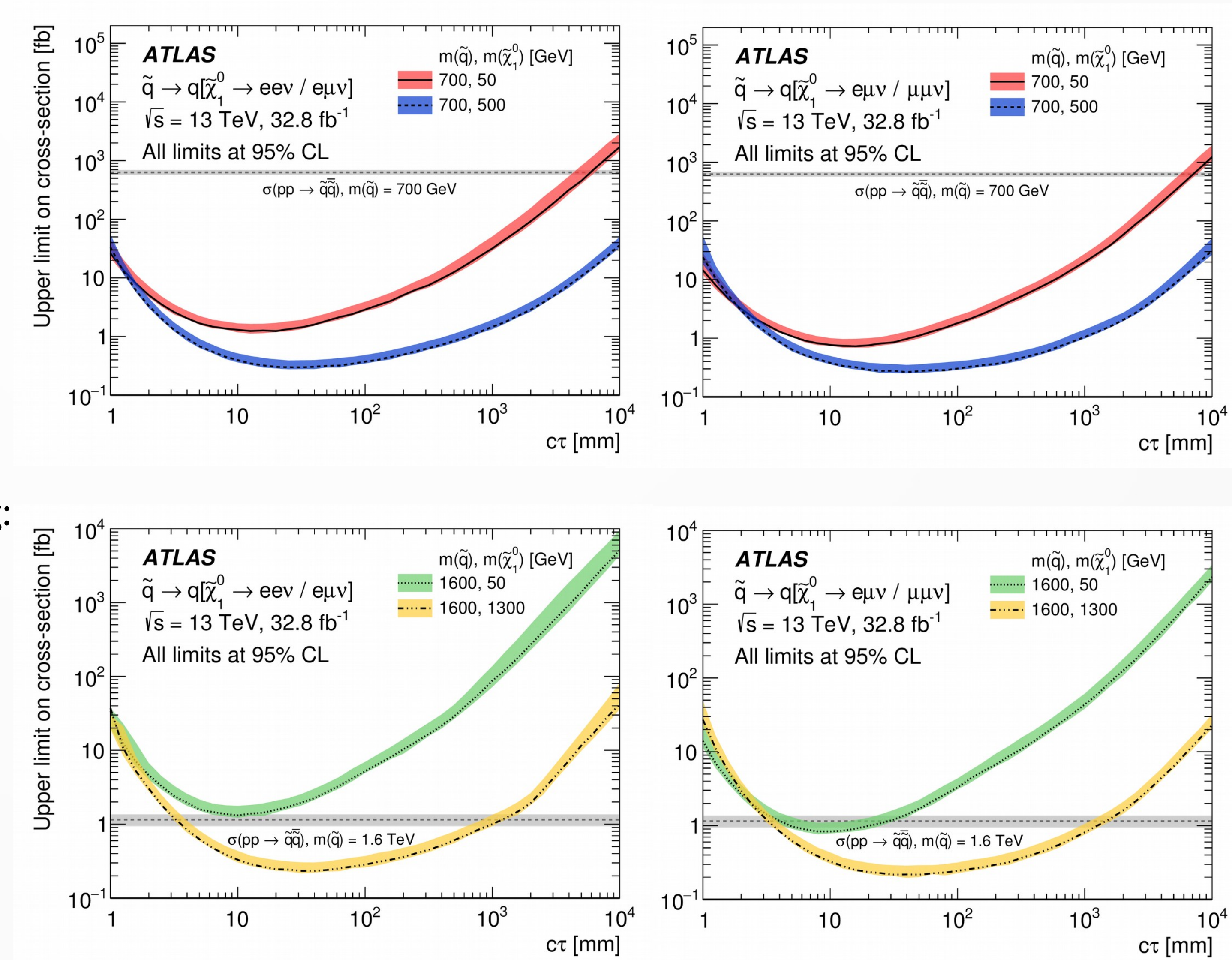
background source	estimate
cosmic-ray muons	$0.27 \pm 0.14\,(\text{stat}) \pm 0.10\,(\text{syst})$
random crossings	$0.0024 \pm 0.0005\,(\text{stat}) \pm 0.0015\,(\text{syst})$

Displaced lepton vertices

Submitted to PLB
arXiv:1907.10037

- No events observed
- Results interpreted in terms of long-lived neutralinos produced via squark pair production:
  - Lifetime generated by small lepton-number-violating RPV couplings
  - RPV decay with one dominant coupling:
    - $\lambda = \lambda_{121}$ or λ_{122}



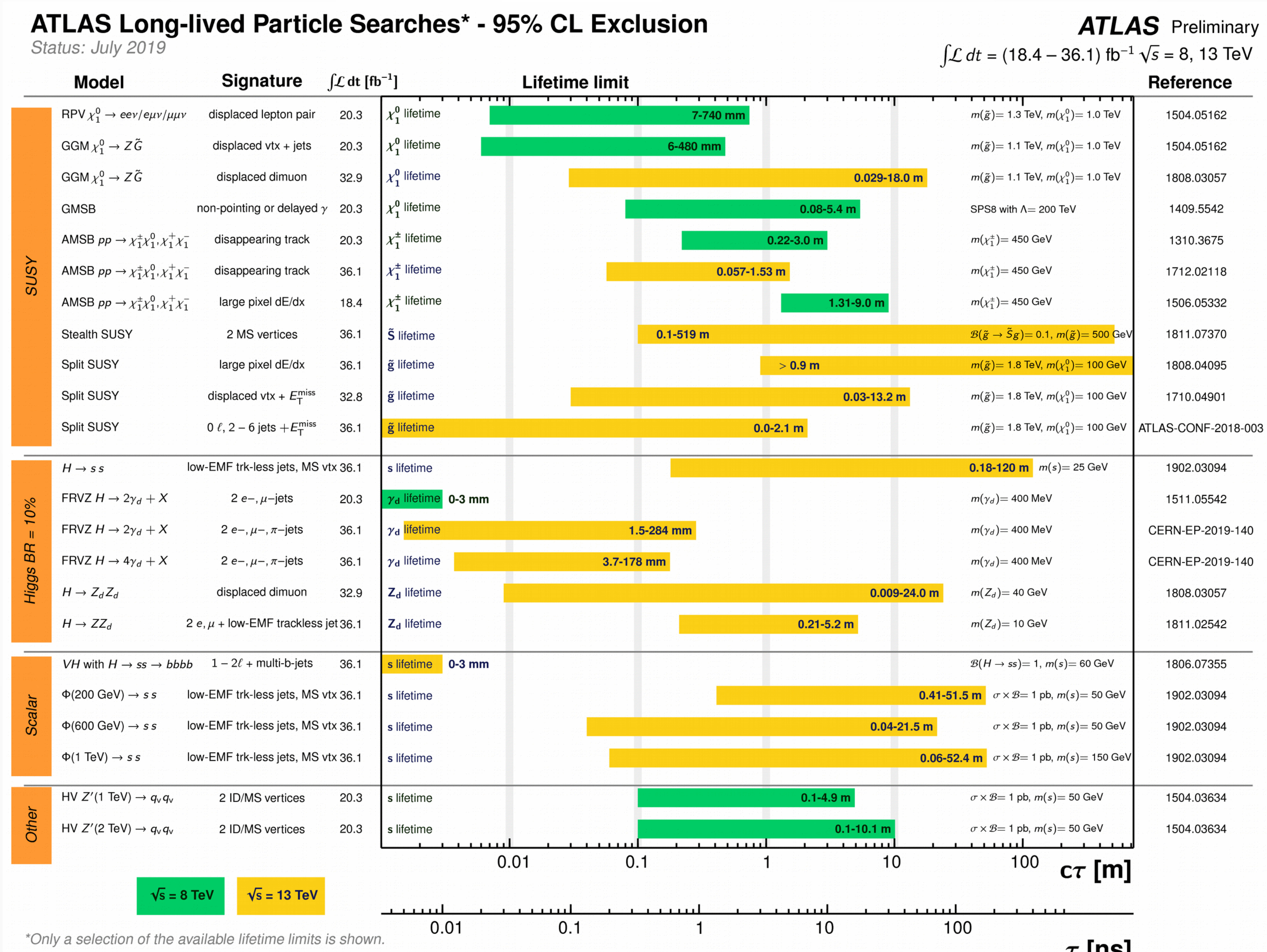


Conclusion

- Both ATLAS and CMS have very extensive and rich programs of searches for new long-lived particles:
  - A few of the most recent results were highlighted here
- These searches often challenge our technical skills and creativity, but they are also very rewarding:
  - Considering "unconventional" signatures, making full use of the excellent capabilities of our detectors and introducing new analysis techniques, lets us probe previously unexplored regions of phase space, and hence significantly increase our discovery potential!
  - Also, more conventional searches are being reinterpreted in the context of models with LLPs to understand their sensitivity to such signatures and their complementarity with dedicated LLP searches
- Stay tuned for more LLP results from the LHC, using the full Run 2 data set and beyond!
  - The systematic exploration of the vast LLP landscape is really beginning in earnest, and this will be a key feature of the hunt for BSM physics in Run 3

Backup

ATLAS LLP search summary



CMS LLP search summary